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FORECASTING THE HATCHING PERIOD OF GRASSHOPPERS

FROM WEATHER DATA

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The earliness or lateness of the hatching period of grasshoppers affects the type and amount of damage to the crop and the timing of control measures. The method most commonly used for determining the status of the hatch has been to have an observer in the field making a spot examination during the months when hatching is likely to occur and then a judgment of what he finds. The accuracy of the data is one of individual judgment.

Laboratory experiments substantiated by field observations have shown the significant effect that temperature has on the rate of embryonic development and the subsequent hatching period.[2] In the field daily maximum air temperatures have been the best criteria of warm weather conditions in their relation to the time of hatching, and their use for unit intervals of 5 days each is better than using monthly averages in this type of analysis. These daily temperature units have therefore been basic to the development of a method for currently predicting the hatching period.

This report pertains to the hatching period of the end or surviving infestation made up of those grasshoppers that have survived all the natural factors that tend to destroy early instar nymphs. It is not the true hatching period for all the infestation, but it is the one that concerns the farmer and the control supervisor.

All the data used in the subsequent analyses were obtained from records of grasshopper collections made in the field by trained observers from 1939 through 1948 in Kansas, Minnesota, Montana, Nebraska, North Dakota, South Dakota, and Wyoming. The collections were made at locations near a Weather Bureau station recording daily maximum and minimum air temperatures and rainfall. The grasshoppers from these collections, made at intervals

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[1] Retired June 30, 1958.

[2] Shotwell, R. L. Life histories and habits of some grasshoppers of economic importance on the Great Plains. U.S. Dept. Agr. Tech. Bul. 774, 47 pp. 1941.

throughout the nymphal period, were separated as to species and number in each instar recorder. In any one locality and year the collection made when most of the specimens were in the last three nymphal instars was the one used to determine the hatching period of a species. In any locality only the primary habitats for the species were used for collecting. If more than one habitat was used at the same station on the same day, the data from all habitats were pooled to obtain the hatching period.

HATCHING CURVE

The hatching curve is formed by plotting the percentages of hatch, 0 to 100 percent, according to the dates upon which they fall. In order to obtain data for statistically analyzing the effect of weather on this curve, it was necessary to assemble all the records of dated collections that showed the percentage of a species found in each nymphal instar. Only those collections were used that were made after hatching was complete and before few or preferably no adults had appeared.

The next step was to prepare table 1 showing the average number of days in each instar for the four economically important species included in this study. These were Melanoplus sanguinipes (F.), M. bivittatus (Say), M. differentialis (Thomas), and M. femurrubrum (De Geer). The averages were obtained from hundreds of individual rearing records of the four species at different constant and varying room temperatures. All through the development and use of this method of forecasting the hatching period, it is the averages that are considered and only approximations that are expected. Six instars are recognized for all four species, although this number will vary from six to seven for differentialis and five to six for the others.

For an explanation of the method used to determine the hatching curve for any one species in a given collection, an example is discussed step by step. To be of use the collection must have been made on a single date and be representative of the general infestation in the vicinity of a weather station.

The information utilized in the example was obtained from collections of differentialis made in five fields in the Belle Fourche area of Butte County, S. Dak., on July 11, 1946. These collections were pooled and identified as to species and the numbers in each instar. The necessary steps are outlined in tables 2 to 4.

In item 3, table 2, the number of specimens in each instar has been converted into a percentage of the total number of specimens collected. Item 1 shows the average number of days in each nymphal instar. There were, in this example, no adults present in any of the five collections, but all six instars were present.

Proceeding with the method, certain logical assumptions are necessarily made. First, a base date such as May 31 is arbitrarily selected, and the date of the collection, July 11, can now be considered as being 41 days after May 31. In table 1 the total number of days for nymphal development of differentialis is 42. Since sixth instar individuals were present in the collections, then 0 percent hatch (table 3) can be considered as being true on that day, 41-42 or

-1 day after May 31, which is May 30. Since first instar individuals were also present in the collections, then 100 percent hatch (table 3) can be considered as being true for no date earlier than the date collection was made, which was July 11, 41 days after May 31.

Had there been no first instar individuals present and if the youngest specimens in the collections were in the second stage of development, then the 100 percent hatch could have been considered as being true for the day 41-6 (days in first instar, item 1, table 2), or 35 days after May 31. Had only the first five instars been present, then the 0 percent hatch would have fallen on the day 31 days preceding July 11 or 41-31 = 10 days after May 31 or June 10. The figure 31 is the sum of the days in the first five instars (item 1, table 2).

Having now filled in the figures for 0 and 100 percent hatches (table 3), we can proceed with the method for determining the number of days after May 31 when 10 to 90 percent hatching had occurred. Table 4 illustrates the method used for continuing the calculations.

Beginning with the 10 percent hatch (step 1, table 4), we can consider 90 percent as being unhatched. Then subtracting from 90 successively the percentages from left to right given in item 3, table 2, we reach a figure 0.4 percent after making the last subtraction of 38.0 in the fourth instar column of item 3, table 2. The next figure in item 3 is 9.3, which cannot be subtracted from 0.4 and still keep positive numbers.

We are now ready to interpolate how far this 0.4 percent cuts into the number of days in the instar which contains this figure 9.3 percent of the collection. It is the fifth instar and has 8 days (item 1, table 2). Continuing under line 1, step 1, table 4, we multiply the 8 days by the fraction 0.4 over 9.3, which equals 0.3 days. We can now assume that all fifth instar specimens have at least gone through an average of $6 + 5 + 5 + 7$ or 23 days (item 1, table 2) in their development. This number 23 is then added to 0.3 days (line 2, step 1, table 4), which equals 23.3 days. Subtracting 23.3 days from 41 days we obtain 17.7 days, which represents the number of days after May 31 when 10 percent had hatched (table 3).

The reasoning here becomes clear if we selected the figure found in the sixth instar column of table 2, which would 1.1 percent hatch equal to the figure 1.1 percent of the collection in the sixth instar. Our reasoning would here be that on this date, July 11, all sixth instar specimens had gone through a total of $6 + 5 + 5 + 7 + 8$ or 31 days' development. Since only 1.1 percent were in the sixth instar, then only 1.1 percent had already existed for at least that length of time, and a 1.1 percent hatch must have occurred by a date 31 days previous to July 11 or 41-31 = 10 days after May 31.

Continuing the method to line 1, step 2, table 4, we next proceed to determine the number of days after May 31 when 20, 30, and 40 percent had hatched. First a 20-percent hatch means 80 percent unhatched and, as before, we proceed to subtract from 80 successive numbers from left to right found in item 3, table 2. The last number subtracted is 31.7, resulting in a remainder of 28.4 percent, from which the next number 38.0 cannot be subtracted without running into negative numbers.

The figure 28.4 now becomes that part of the figure 38.0, which is interpolated into the number of days for the fourth instar, which is 7. That part is 28.4 over 38.0 multiplied by 7, equaling 5.2 days (line 2, step 2, table 4). Again we assume that all the fourth instar specimens have gone through at least $6 + 5 + 5 = 16$ days of development, to which is added 5.2 days, which equals 21.2 days. This last figure is then subtracted from 41, giving 19.8 as the number of days after May 31 when 20 percent had hatched, as shown in table 3.

It is not necessary to go through all these subtractions to obtain each of the next two figures for the 30 and 40 percent hatch. Instead we can successively subtract 10 from the remainder 28.4 in line 1, step 2, table 4, until it cannot be subtracted further without running into negative numbers. Thus $28.4-10 = 18.4$ and $18.4-10 = 8.4$, which is as far as we can go. Further interpolation into the number of days in the fourth instar consists in multiplying 7 days by 18.4 over 38.0 and 8.4 over 38.0, which equals 3.4 and 1.5 days, respectively. These numbers are, in turn, added to the total of 16 days in the first three instars, equaling 19.4 and 17.5 days, respectively. Subtracting these from 41 we obtain 21.6 days for the 30 percent hatch and 23.5 days for the 40 percent hatch, as given in table 3, for the number of days after May 31 when these percentages of hatch had occurred.

We are still left with the calculations for a 50 to 90 percent hatch, and the procedure is the same as shown in steps 3 and 4, table 4.

Table 3 has now all the data necessary to plot a hatching curve for the end population of differentialis in Butte County, S Dak., in 1946 The YY axis or ordinates represent the percentage of hatch 0, 10, 20, 30, ... 100 percent and the abscissa or XX axis represents the number of days after May 31 converted to a period of time marked by actual dates. Hatching curves show a marked similarity in form, with the part of the curve between 10 and 90 percent hatch being in an almost straight line. Before the former and beyond the latter points, the curves trail off, indicating that, at the beginning and end of the period, hatching is somewhat prolonged and dragged out. This phenomenon has been verified by direct observation.

Hatching Period of Melanoplus sanguinipes

In order to show the wide variation in the hatching period of sanguinipes and to compare this with temperature and rainfall, figure 1 was prepared from data accumulated between 1939 and 1948, inclusive. The vertical axes show the degrees of daily maximum air temperature and inches of rainfall on the left and the number of accumulative degrees above 60° F. of daily maximum temperatures on the right. This latter measurement had been used before with some precision to predict the beginning of the hatch of sanguinipes, bivittatus, and differentialis. The horizontal axes show the period of time, March 2 to June 29 or July 29, inclusive, divided into equal intervals of 5 days.

All data were divided into eight groups on the basis of when 10 percent of the hatch had taken place. From the top left-hand corner of figure 1 to the bottom right-hand corner, the grouping for the time when 10 percent had hatched was as follows: (1) April 21-30, (2) May 1-10, (3) May 11-20, (4) May 21-30, (5) May 31-June 9, (6) June 10-19, (7) June 20-29, and (8) June 30-July 9. The two vertical dotted lines in each grouping show the average period on the
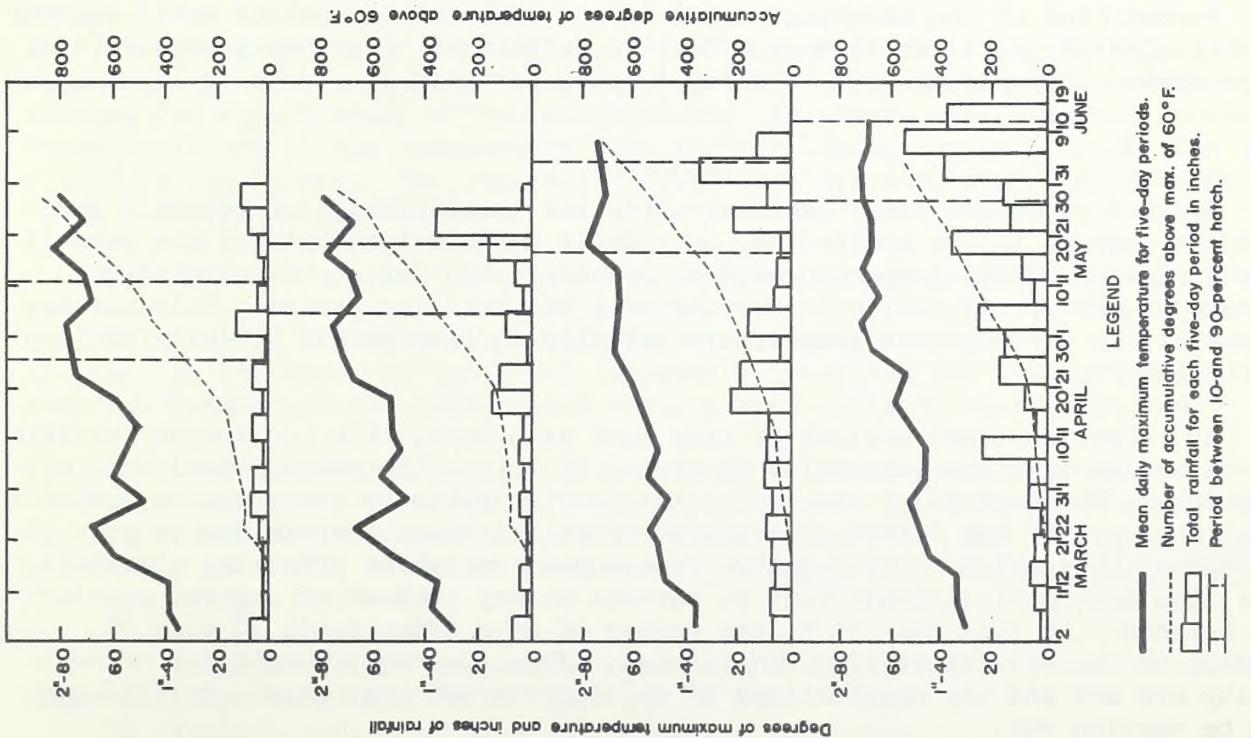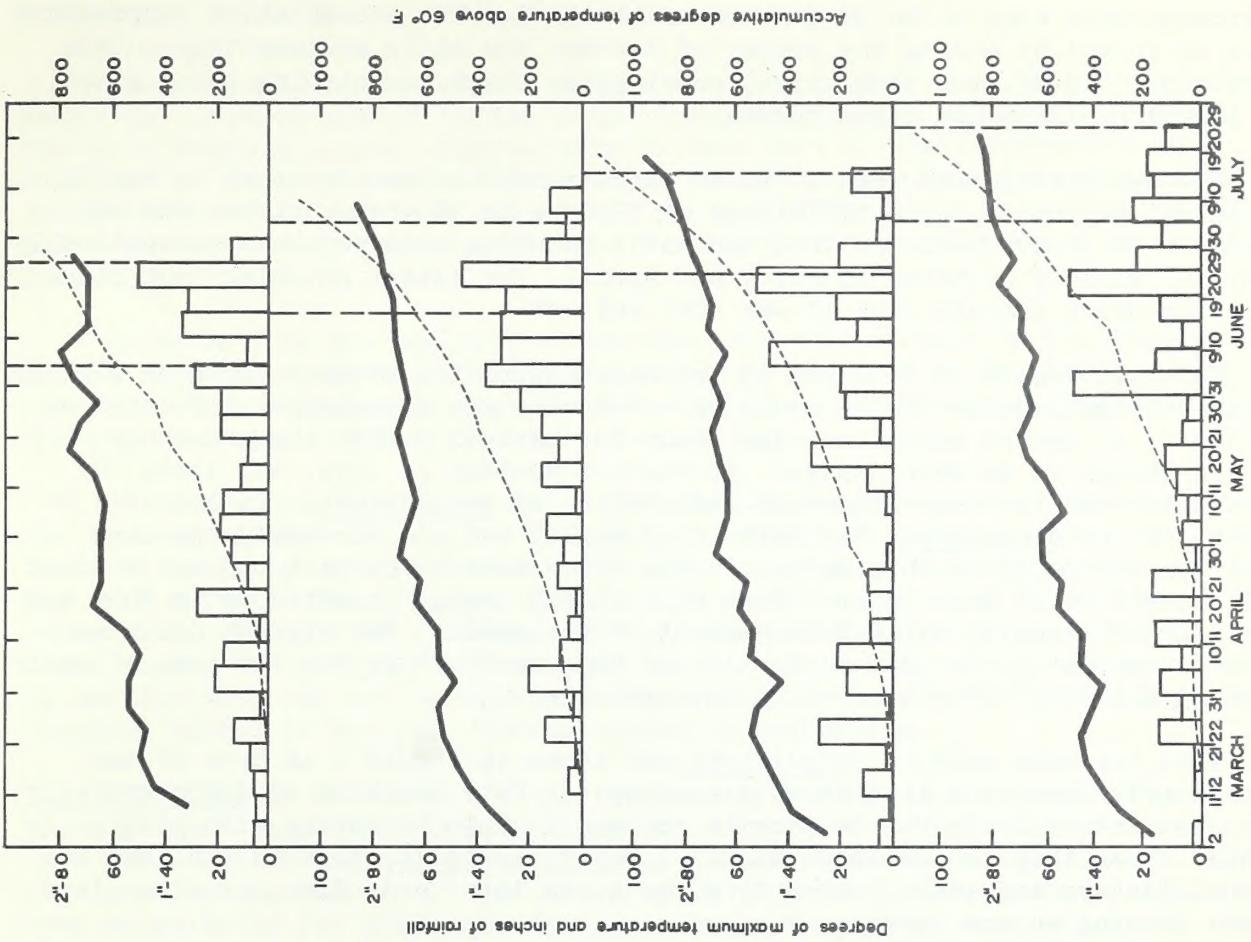
Figure 1.--Hatching period of Melanoplus sanguinipes in relation to air temperature and rainfall.

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horizontal axis when 10 to 90 percent had hatched. The accumulative temperature curve is formed by adding the number of degrees the daily maximum temperature rises above 60° F., the theoretical point below which no hatching takes place. The legend explains the other curves.

The earliest period when 10 to 90 percent hatched was April 26 to May 11, the latest July 5 to 23, a difference of 70 days or 10 weeks between the two periods. It should be noted that the early hatching occurred when exceptionally warm, dry weather occurred in March and April. The latest hatching took place when from March through June it was cool and wet.

This difference of 10 weeks in the hatching period between years or regions means that small grain can be newly sprouted when the grasshopper infestations develop or it can be headed out and ready for harvest before the grasshoppers are big enough to do much damage. In eastern Montana in 1939, two areas 100 miles apart had the same degree of infestation of sanguinipes. In one area 90 percent of the sanguinipes had hatched by May 15 and all the newly sprouted grain was destroyed by this date. In the other area 90 percent had not hatched until June 8 or 24 days later. Here only slight damage occurred up to July and then migrating adults damaged 20 percent of the heads. The average daily maximum air temperature for March, April, and May was 60.7° F. for the area of early hatching and 53.4° for the area of late hatching.

What has been said of sanguinipes and shown in figure 1 is true of any economically important species of grasshopper. Late hatching of differentialis in south-central South Dakota permits the small grain to mature with little damage. When this is cut about August 1, differentialis, then in the last two nymphal instars and adult, moves from the grain into corn, flax, or other late crops, causing severe losses.

Forewarning of the hatching period in any infestation enables early control of the infestation, which is more effective, efficient, and timely than waiting to protect a crop in answer to a farmer's plea for help.

Method

Because other analyses[3] demonstrated that the inclusion of rainfall gave no added support to the prediction, only daily maximum temperatures are used in this analysis. These temperatures measure warmth and depict the warming-up process in the spring, which in turn affects the hatching period. This pattern of weather is a continuous temperature variable in time marked by daily maxima and minima.

By selecting equal periods of time such as 5 days, this continuous variable can be broken up into equal units of time. By taking the average daily maximum temperature for each 5-day interval, it is now possible to use these in a statistical analysis of the effect of temperature on hatching, wherein use is made of orthogonal polynomials. They become independent variables affecting a hatching date, the dependent variable when 70 percent or any percent of a given species has hatched. In this case it is the number of days after April 30 when 70 percent of the end infestation had hatched. Thus the requirements for orthogonality are met and the computations of multipliers and regression coefficients can be carried out.

[3] Shotwell, R. L. Unpublished data.

Analysis of Variance

Since this is a statistical analysis of correlated temperature and hatching data, the class or set of things being discussed must be clearly understood. The term hatching period applies only to that part of the infestation that survives to become a problem of control, damage to crop, and perpetuation of the infestation. This has been called the end infestation and is made up of all those survivors that have escaped all factors that tend to destroy newly hatched nymphs.

In table 5 is the analysis of variance for the testing of the significance of the regression for each of the four species included in this study. The F values for the temperature regression are highly significant, being well above the 1-percent level (99 to 1 odds) in every case.

It can be concluded that daily maximum temperatures are a measure of heat and have an additive effect on the rate of embryonic development. Laboratory tests in hatching eggs at controlled temperatures have already proved that heat has this effect. This finding permitted the assumption that the effect of heat on hatching at any time is independent of the amount of heat occurring at any other time. The analysis of variance has now given high significance to the assumption that use can be made of orthogonal polynomials for predicting the hatching period of the end infestations of grasshoppers.

According to Houseman,[4] "This is done by the application of Fisher's device which gives a regression curve that shows the effect on hatching of a unit change in a given meteorological element at any time during the growing season." For this problem the number of days after April 30 when 70 percent had hatched has been substituted for yield and the unit change in a given meteorological element is 1 degree of average daily maximum temperature for a 5-day interval.

These regression curves are shown in figure 2 for each of the four species. Houseman[5] gives a method for interpreting these curves. This involves the testing for significance of the coefficients, the Ta's, which measure various characteristics of the temperature distribution during the periods of time included in the curves. The regression coefficients are shown in table 6a and their significance is tested by using the t values in table 6b.

The Ta_0 is a measure of the effect of the total temperature for the periods indicated for the curves in figure 2. According to table 6b, the Ta_0 regression coefficients are statistically significant, which means that, for the four species, an increase in the total temperature shortens the time after April 30 when development of the infestation takes place. This is to be expected.

The second measure, Ta_1, is proportional to the average increase or decrease of temperature per 5-day interval during the periods included in the curves. The Ta_1 regression coefficients are statistically significant for both sanguinipes, especially the early hatching ones, and bivittatus, but not for differentialis and femurrubrum (table 6b).

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[4] Houseman, E. E. Methods of computing a regression of yield on weather. Iowa Agr. Expt. Sta. Res. Bul. 302, pp. 863-904. 1942.
[5] Ibid.
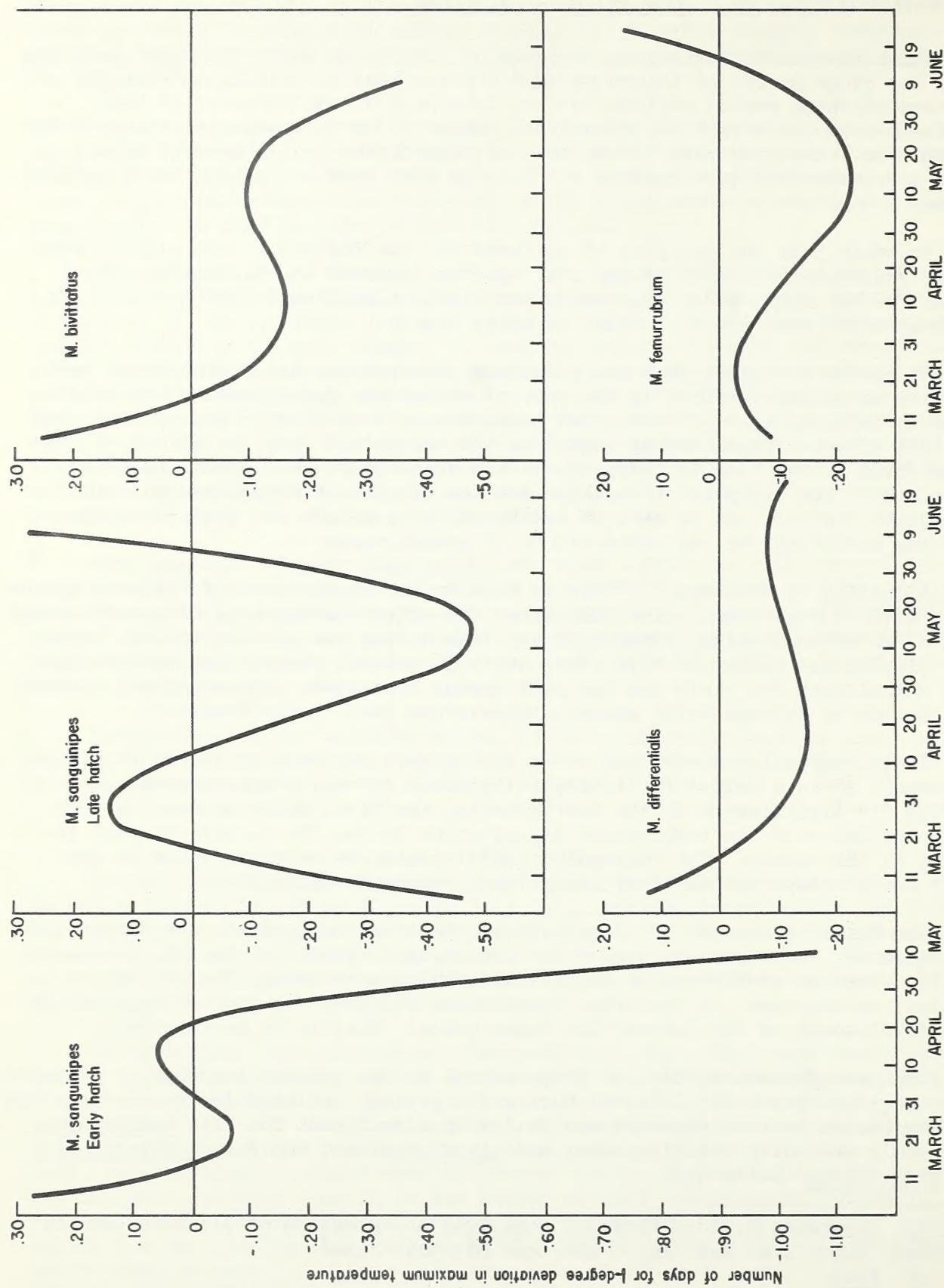
Figure 2.--Average effect of 1 degree of daily maximum temperature on number of days after April 30 when 70 percent of end infestation had hatched.

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Both sanguinipes and bivittatus under the same conditions will hatch 2 or 3 weeks earlier than differentialis or femurrubrum. This is due to the fact that some eggs of both sanguinipes and bivittatus have completed most of their embryonic development in the fall. It is possible for an early warm spell to bring on a partial hatch, which with rapidly rising temperatures can go on to a completed early hatch or with decreasing temperatures can be wiped out with few or no survivors left for the end infestation. Therefore, the hatching of these two species is more affected by these temperature changes than the later hatching of differentialis and femurrubrum. Table 6b also shows that the effect of temperature change is of greater significance for the early hatching than the late hatching sanguinipes. This is also shown in figure 1 by the fact that the more gradual the rise of the curve for the average maximum temperature for the 5-day intervals, the later the hatching period.

The Ta_2 measures the effect of the distribution of the temperature during the middle of the curve. This is significant for only the early hatching sanginipes. Between the time the spring weather first warms up enough to start embryonic development and the early hatching of sanguinipes the last half of April and first of May, the period is so short that a lot of heat has to be packed into a relatively few days. This means that heat in the middle of the period is important also in effecting an early hatch. It is not so important for the other species, including late hatching sanguinipes.

Heat in the middle of the period has some effect on femurrubrum, as shown by the t value for the Ta_2 of this species. Heat in the first half of May can bring on a partial hatch of differentialis, which is subsequently destroyed by the cold, wet weather that usually follows later into June. This affects the hatching period of the end infestation by killing off the early hatching nymphs. In other words, warm weather in early May can delay the development of the end infestation if it is followed by cold, wet conditions.

The Ta_3 (table 6a) whether positive or negative determines the shape of the graphs in figure 2. When positive, the graph reaches a maximum the first half of the season and a minimum the last half of the season, and vice versa. In comparing the early and late developing sanguinipes, there is a difference between a negative and positive Ta_3 regression coefficient, respectively. This means that the regression curves are reversed in respect to each other.

For the early development of sanguinipes infestations, above-average temperature tends at first to shorten the time to hatching, then increase the time if colder weather follows or rapidly shortens it if much warmer weather occurs. For the late development, the trend is definitely from a shortening to a lengthening of the time by the early above-average temperature, since colder weather does follow. Then later the warming-up process takes on greater significance in shortening the time to the development of the infestation.

For bivittatus the shape of the curve is similar to that of early developing sanguinipes. However, for bivittatus both minimum and maximum points on the graph are below the zero line. Above-average temperatures before March 16 may delay the development of the end infestation unless warm weather continues after March 16, when above-average temperature will always have a shortening effect on the time up to the development of the infestation.

For _differentialis_, a late hatching species, the curve is rather flat, indicating that as a rule there is very little difference when the heat comes, just so long as it is continuous and there is enough of it to effect a hatch. Both minimum and maximum points on the graph are below the zero line.

The curve for _femurrubrum_ shows a maximum in the first half and a minimum in the second half of the period of the curve, both both are below the zero line. The greatest effect of a 1-degree change in temperature comes as a negative effect in the second half. This means that the greater the heat at that time, May 16-20, the earlier the development of the infestations.

Tables for Predicting the Hatch of the End Infestation

Tables 7a and b to 11a and b, inclusive, are for the purpose of predicting when the development of the end infestation will take place. This is measured by the period when 0 to 100 percent of the grasshoppers making up the infestation will have hatched.

In column 1 of the "a" part of the tables are shown the inclusive dates of the 5-day intervals. These dates are to be used in connection with current weather data in column 3. Column 2 shows the average daily maximum temperatures for the intervals for all the data used in the analysis of a species, and these figures are treated as constants. In column 3 are the current average daily maximum temperatures for the intervals in column 1, computed from data obtained from the weather station in the area. The deviation of these figures from those in column 2 is recorded in column 4, with strict attention paid to the proper sign. These deviations in degrees are then multiplied by the figures in column 5, which represent days and show the effect of 1 degree. Again positive and negative signs must be considered carefully. The results of these multiplications are then totaled in column 6 for the pertinent interval. Signs must again be considered.

The result, which is in days, is added to, if positive, or is subtracted from, if negative, the dates shown in the "b" part of the table. This then becomes the predicted hatching period when 0 to 100 percent of the end infestation will have hatched. As the season progresses and the weather data for more 5-day intervals are included, this prediction will change with the computations in columns 4, 5, and 6 if the current weather shown in column 3 continues to differ with the average figures given in column 2. Thus any marked difference or change in weather will show up at once in the prediction. The unfolding effect of the spring temperature pattern on the seasonal development of an infestation can be computed with a reasonable amount of confidence up to any time as the season progresses.

How Prediction Tables Are Used

Two examples, one of early and the other of late hatching _singuinipes_, have been selected to illustrate how the prediction tables are used. Both examples are actual cases of the hatching periods of _sanguinipes_. The case of the early hatching was at Circle, Mont., in 1939, when 10 to 90 percent of the hatch took place between May 2 and 16, inclusive. The case of the late hatching was at Carson, N. Dak., in 1945, when 10 to 90 percent of the hatch did not take place until July 2 to 23, inclusive. The average maximum temperatures for the 5-day

intervals at each of the two places are listed in table 12. These columns of figures now become column 3 of the prediction tables 7a and 8a, depending on which column fits the more closely.

From the middle of April on one can readily see that the average daily maximum temperature pattern or trend for Circle, Mont., 1939 fits the average maximum temperatures shown in column 2, table 7a, and that for Carson, N. Dak., 1945 fits those in column 2, table 8a. Therefore, in the last columns, tables 13 and 14, are the computations for the prediction of the hatching period.

The prediction in table 13 for the early hatch of sanguinipes from the start does not vary much from the actual hatching period. In table 14, however, the prediction for late hatching on April 5 begins with the average dates June 7-26 and gets later and later with each 5-day interval until on June 4 it is July 8-27, or 6 days later than the actual. Then 5 days later on June 9, the limit of the table, the prediction drops back to July 3-22 as compared with the actual July 2-23.

It is not practical to use the 0 to 100 percent hatch, as there is a much greater variability in the first and last 10 percent of the hatch than any 10 percent between 10 and 90. Hatching is prolonged more for the first and last 10 percent.

Summary

The earliness or lateness of the hatching period of grasshoppers affects the type and amount of damage to the crop and the timing of control measures. Laboratory experiments substantiated by field observations have shown the significant effect that temperature has on the rate of embryonic development and the subsequent hatching period. The average daily maximum air temperatures for unit intervals of 5 days each were used in the development of a method for currently predicting the hatching period of four economically important species of grasshoppers--Melanoplus sanguinipes (F.), M. bivittatus (Say), M. differentialis (Thomas), and M. femurrubrum (De Geer). These units became the independent variables affecting a hatching date, the dependent variable given as the number of days after April 30 when 70 percent of the end infestation had hatched. The term "end infestation" applies to the surviving infestation made up of those grasshoppers that have survived all the natural factors that tend to destroy early instar nymphs. It is not the true hatching period for all the infestation, but it is the one that concerns the farmer and the control supervisor.

A method is described for obtaining figures for the dependent variables, based on grasshopper collections made during the nymphal development period and a knowledge of the average number of days in each instar. Thus the requirements for orthogonality were met and the computations of multipliers and regression coefficients carried out.

Laboratory tests in the hatching of eggs at controlled temperatures had already proved that heat had an additive effect on the rate of embryonic development. This permitted an assumption that the effect of heat on hatching at any time is independent of the amount of heat occurring at any other time. A regression curve was developed for each of the four species. It showed the average effect of a unit change of 1 degree of average daily maximum temperature for a 5-day interval on the number of days after April 30 when 70 percent of the end infestation had hatched.

These averages or multipliers can be used in setting up tables for predicting hatching dates for each of the four species, employing deviations from current maximum temperatures. The current maximum temperatures can be obtained from the Weather Bureau station. Information in these tables can be used to supplant or supplement field observations.

Table 1.--Average number of days in each instar

Melanoplus species	Instars						Total
	1	2	3	4	5	6	
	Days	Days	Days	Days	Days	Days	Days
sanguinipes----------	8	6	6	7	8	9	44
bivittatus----------	8	6	7	9	9	10	49
differentialis-------	6	5	5	7	8	11	42
femurrubrum----------	9	7	7	8	10	15	56

Table 2.--Specimens of Melanoplus differentialis collected in each stage of development

Items	Instars						Adults	Total
	1	2	3	4	5	6		
Days in each stage number--	6	5	5	7	8	11	--	--
Specimens collected do------	50	175	358	429	105	13	0	1,130
Total specimens collected----percent-	4.4	15.5	31.7	38.0	9.3	1.1	0	100

Table 3.--Days after May 31 when certain percentages of Melanoplus differentialis had hatched

Hatch (percent)	Days
	Number
0 -------------	- 1.0
10 -------------	17.7
20 -------------	19.8
30 -------------	21.6
40 -------------	23.5
50 -------------	25.3
60 -------------	26.8
70 -------------	28.4
80 -------------	30.0
90 -------------	33.2
100 -------------	41.0

Table 4.--Steps in calculating number of days after May 31
        when certain percentages of Melanoplus differentialis
                          had hatched

Steps	Calculations
1 ────────	$90-4.4-15.5-31.7-38.0=0.4$ percent
	$\dfrac{0.4}{9.3}$x8=0.3; 0.3+23=23.3; 41-23.3=17.7
2 ────────	$80-4.4-15.5-31.7=28.4$ percent
	$\dfrac{28.4}{38.0}$x7=5.2; 5.2+16=21.2; 41-21.2=19.8
	$\dfrac{18.4}{38.0}$x7=3.4; 3.4+16=19.4; 41-19.4=21.6
	$\dfrac{8.4}{38.0}$x7=1.5; 1.5+16=17.5; 41-17.5=23.5
3 ────────	$50-4.4-15.5=30.1$ percent
	$\dfrac{30.1}{31.7}$x5=4.7; 4.7+11=15.7; 41-15.7=25.3
	$\dfrac{20.1}{31.7}$x5=3.2; 3.2+11=14.2; 41-14.2=26.8
	$\dfrac{10.1}{31.7}$x5=1.6; 1.6+11=12.6; 41-12.6=28.4
	$\dfrac{0.1}{31.7}$x5=0; 0+11=11.0; 41-11.0=30.0
4 ────────	$10-4=5.6$ percent
	$\dfrac{5.6}{15.5}$x5=1.8; 1.8+6=7.8; 41-7.8=33.2

Table 5.--Analysis of variance of hatching dates for 4 grasshopper species

Source of variation	Degrees freedom	Sum of squares	Mean square	F value[1]	F value 5 percent	1 percent
Melanoplus sanguinipes (early hatching)						
Total --------	24	2,198	--	--	--	--
Temperature regression--	4	1,465	366.25	11.57**	2.87	4.43
Deviation from regression--	20	633	31.65	--	--	--
Melanoplus sanguinipes (late hatching)						
Total --------	30	5,380	--	--	--	--
Temperature regression--	4	3,212	803.0	9.62**	2.74	4.14
Deviation from regression--	26	2,168	83.4	--	--	--
Melanoplus bivittatus						
Total --------	38	8,187	--	--	--	--
Temperature regression--	4	6,597	1,649	36.64**	2.65	3.93
Deviation from regression--	34	1,590	45	--	--	--
Melanoplus differentialis						
Total --------	27	2,875	--	--	--	--
Temperature regression--	4	2,192	548	18.26**	2.80	4.26
Deviation from regression--	23	683	30	--	--	--
Melanoplus femurrubrum						
Total --------	37	6,375	--	--	--	--
Temperature regression--	4	4,289	1,072	17.01**	2.67	3.97
Deviation from regression--	33	2,086	63	--	--	--

[1] ** = 1-percent level of significance.

Table 6a.--Regression coefficients where time of hatching is related to properties of temperature distribution during March 2-June 24

Melanoplus species	Regression Coefficients			
	Ta_0	Ta_1	Ta_2	Ta_3
sanguinipes (early hatching)--	-0.126285	-0.029896	-0.020392	-0.002009
sanguinipes (late hatching)---	- .155716	- .003799	.001096	.000467
bivittatus -------------------	- .102086	- .008109	.000925	- .000925
differentialis ---------------	- .088386	- .005039	.001264	- .000905
femurrubrum ------------------	- .100526	- .000499	.001803	.001777

Table 6b.--Values of t for testing significance of regression coefficients

Melanoplus species	Degrees freedom	Calculated t values of regression coefficients[1]			
		Ta_0	Ta_1	Ta_2	Ta_3
sanguinipes (early hatching)---------	20	4.09**	4.58**	3.77**	2.05+
sanguinipes (late hatching)--------	26	5.48**	2.00+	.68	4.28**
bivittatus----------	34	4.71**	6.63**	.75	1.37
differentialis------	23	6.01**	.89	1.30	.75
femurrubrum---------	33	5.69**	.09	1.90+	1.62

[1] ** and + = 1- and 10-percent level of significance, respectively.

Table 7a.--Prediction of early hatching of Melanoplus sanguinipes as to dates
when 0 to 100 percent will have hatched

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Devia- tion $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	31.0			0.284		
7-11----	38.0			.082		
12-16----	39.3			- .031		
17-21----	55.3			- .073		
22-26----	65.5			- .066		
27-31----	48.1			- .028		
April 1-5----	58.0			.018		
6-10----	52.4			.055		
11-15----	54.2			.061		
16-20----	57.1			.017		
21-25----	69.7			- .098		
26-30----	75.2			- .304		
May 1-5----	76.2			- .620		
6-10----	67.6			-1.067		

1/ Results of column 6, sum of $a(t-\bar{t})$, added to or subtracted from
dates in table 7b when 0 to 100 percent will have hatched.

Table 7b.--Average and predicted hatching dates for Melanoplus sanguinipes
(early hatching) when 0 to 100 percent will have hatched

Hatch (percent)	Average date	Predicted date
0 -------------	April 29 -------------	
10 -------------	May 6 ---------------	
20 -------------	May 8 ---------------	
30 -------------	May 9 ---------------	
40 -------------	May 10 -------------	
50 -------------	May 12 -------------	
60 -------------	May 13 -------------	
70 -------------	May 15 -------------	
80 -------------	May 16 -------------	
90 -------------	May 19 -------------	
100 -------------	May 25 -------------	

Table 8a.--Prediction of late hatching of Melanoplus sanguinipes as to dates
when 0 to 100 percent will have hatched

5-day interval	Average maximum temperature $\overline{t}$	Current average maximum temperature t	Devia-tion $(t-\overline{t})$	Effect of 1-degree deviation a	Sum of $a(t-\overline{t})$	Hatching dates[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	26.0			-0.473		
7-11----	33.4			- .215		
12-16----	41.3			- .034		
17-21----	47.8			.079		
22-26----	50.1			.134		
27-31----	52.7			.140		
April 1-5----	47.9			.106		
6-10----	50.5			.041		
11-15----	53.9			- .044		
16-20----	61.9			- .142		
21-25----	59.8			- .242		
26-30----	67.0			- .335		
May 1-5----	67.3			- .412		
6-10----	62.3			- .463		
11-15----	65.7			- .480		
16-20----	70.8			- .452		
21-25----	70.7			- .371		
26-30----	67.3			- .227		
31-4----	70.9			- .011		
June 5-9----	71.9			.287		

[1] Results of column 6, sum of $a(t-\overline{t})$, added to or subtracted from
dates in table 8b when 0 to 100 percent will have hatched.

Table 8b.--Average and predicted hatching dates for Melanoplus sanguinipes
(late hatching) when 0 to 100 percent will have hatched

Hatch (percent)	Average date	Predicted date
0 --------------	May 26 ------------	
10 --------------	June 7 -----------	
20 --------------	June 12 ----------	
30 --------------	June 14 ----------	
40 --------------	June 16 ----------	
50 --------------	June 18 ----------	
60 --------------	June 20 ----------	
70 --------------	June 22 ----------	
80 --------------	June 24 ----------	
90 --------------	June 26 ----------	
100 --------------	July 5 -----------	

Table 9a.--Prediction of hatching of Melanoplus bivittatus as to dates when 0 to 100 percent will have hatched

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Deviation $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	25.8			0.261		
7-11----	31.0			.129		
12-16----	42.7			.027		
17-21----	48.7			- .049		
22-26----	53.6			- .102		
27-31----	53.8			- .136		
April 1-5----	51.5			- .154		
6-10----	54.0			- .158		
11-15----	55.8			- .153		
16-20----	64.6			- .140		
21-25----	62.7			- .125		
26-30----	68.0			- .109		
May 1-5----	66.6			- .096		
6-10----	62.7			- .089		
11-15----	66.9			- .092		
16-20----	74.2			- .107		
21-25----	73.6			- .138		
26-30----	67.5			- .189		
31- 4----	73.6			- .261		
June 5-9----	75.8			- .359		

1/ Results of column 6, sum of $a(t-\bar{t})$, added to or subtracted from dates in table 9b when 0 to 100 percent will have hatched.

Table 8b.--Average and predicted hatching dates for Melanoplus bivittatus when 0 to 100 percent will have hatched

Hatch (percent)	Average date	Predicted date
0 --------------	May 12 ------------	
10 -------------	June 4 ------------	
20 -------------	June 11 ----------	
30 -------------	June 13 ----------	
40 -------------	June 15 ----------	
50 -------------	June 17 ----------	
60 -------------	June 19 ----------	
70 -------------	June 22 ----------	
80 -------------	June 24 ----------	
90 -------------	June 28 ----------	
100 -------------	July 6 -----------	

Table 10a.--Prediction of hatching of Melanoplus differentialis as to dates when 0 to 100 percent will have hatched

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Devia- tion $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	29.4			0.134		
7-11----	35.4			.064		
12-16----	45.2			.006		
17-21----	50.5			- .041		
22-26----	56.3			- .078		
27-31----	57.8			- .107		
April 1-5----	53.1			- .128		
6-10----	56.4			- .142		
11-15----	58.3			- .149		
16-20----	66.6			- .151		
21-25----	64.4			- .150		
26-30----	69.8			- .144		
May 1-5----	66.3			- .136		
6-10----	62.6			- .126		
11-15----	67.0			- .116		
16-20----	73.4			- .106		
21-25----	73.7			- .097		
26-30----	67.8			- .090		
31-4----	72.3			- .086		
June 5-9----	76.0			- .085		
10-14----	72.9			- .090		
15-19----	72.1			- .100		
20-24----	75.0			- .116		

1/ Results of column 6, sum of $a(t-\bar{t})$, added to or subtracted from dates in table 10b when 0 to 100 percent will have hatched.

Table 10b.--Average and predicted hatching dates for Melanoplus differentialis when 0 to 100 percent will have hatched

Hatch (percent)	Average date	Predicted date
0 ---------------	June 5 ------------	
10 ---------------	June 13 -----------	
20 ---------------	June 17 -----------	
30 ---------------	June 19 -----------	
40 ---------------	June 21 -----------	
50 ---------------	June 22 -----------	
60 ---------------	June 24 -----------	
70 ---------------	June 26 -----------	
80 ---------------	June 28 -----------	
90 ---------------	June 30 -----------	
100 ---------------	July 9 -----------	

Table 11a.--Prediction of hatching of Melanoplus femurrubrum as to dates when 0 to 100 percent will have hatched

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Devia-tion $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	26.8			-0.093		
7-11----	31.6			- .057		
12-16----	42.4			- .035		
17-21----	48.2			- .025		
22-26----	52.0			- .026		
27-31----	53.7			- .035		
April 1-5----	51.1			- .052		
6-10----	52.6			- .074		
11-15----	56.6			- .100		
16-20----	65.1			- .127		
21-25----	62.6			- .154		
26-30----	68.9			- .180		
May 1-5----	65.2			- .202		
6-10----	61.7			- .218		
11-15----	66.2			- .227		
16-20----	73.6			- .228		
21-25----	72.7			- .217		
26-30----	66.7			- .194		
31-4----	73.2			- .157		
June 5-9----	76.0			- .104		
10-14----	71.9			- .033		
15-19----	72.1			.058		
20-24----	73.7			.170		

[1] Results of column 6, sum of $a(t-\bar{t})$, added to or subtracted from dates in table 11b when 0 to 100 percent will have hatched.

Table 11b.--Average and predicted hatching dates for Melanoplus femurrubrum when 0 to 100 percent will have hatched

Hatch (percent)	Average date	Predicted date
0 -------------	May 30 ------------	
10 -------------	June 14 -----------	
20 -------------	June 18 -----------	
30 -------------	June 20 -----------	
40 -------------	June 22 -----------	
50 -------------	June 24 -----------	
60 -------------	June 26 -----------	
70 -------------	June 28 -----------	
80 -------------	June 30 -----------	
90 -------------	July 4 ------------	
100 -------------	July 16 -----------	

Table 12.--Average daily maximum temperatures for 5-day intervals at Circle, Mont., 1939 and Carson, N. Dak., 1945

5-day intervals	Average maximum temperatures (° F.)	
	Circle, Mont., 1939	Carson, N. Dak., 1945
March 2-6 -------------	24.8	21.4
7-11 -------------	35.2	44.8
12-16 -------------	23.4	52.4
17-21 -------------	54.0	60.4
22-26 -------------	66.8	58.4
27-31 -------------	50.8	52.0
April 1-5 -------------	55.6	39.2
6-10 -------------	49.8	60.0
11-15 -------------	53.6	51.0
16-20 -------------	56.6	54.2
21-25 -------------	70.0	48.8
26-30 -------------	80.0	58.0
May 1-5 -------------	78.2	61.2
6-10 -------------	64.6	52.2
11-15 -------------	75.0	50.4
16-20 -------------	79.8	55.8
21-25 -------------	62.2	70.0
26-30 -------------	82.4	60.0
31-4 -------------	----	56.0
June 5-9 -------------	----	54.0

Table 13.--Prediction of hatching period for Melanoplus sanguinipes at Circle, Mont., 1939

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Devia- tion $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates (10-90%)[1]
	° F.	° F.	° F.	Days	Days	May
March 2-6----	31.0	24.8	-6.2	0.284	-1.76	4-17
7-11----	38.0	35.2	-2.8	.082	-1.99	4-17
12-16----	39.3	23.4	-15.9	- .031	-1.50	4-17
17-21----	55.3	54.0	-1.3	- .073	-1.40	4-17
22-26----	65.5	66.8	1.3	- .066	-1.49	4-17
27-31----	48.1	50.8	2.7	- .028	-1.56	4-17
April 1-5----	58.0	55.6	-2.4	.018	-1.61	4-17
6-10----	52.4	49.8	-2.6	.055	-1.75	4-17
11-15----	54.2	53.6	- .6	.061	-1.79	4-17
16-20----	57.1	56..6	- .5	.017	-1.80	4-17
21-25----	69.7	70.0	.3	- .098	-1.82	4-17
26-30----	75.2	80.0	4.8	- .304	-3.28	2-15
May 1-5----	76.2	78.2	2.0	- .620	-4.52	1-14
6-10----	67.6	64.6	-3.0	-1.067	-1.32	4-17

1/ Average dates for 10-90% hatch - May 6-19, from table 7b. Actual dates for 10-90% hatch, Circle, Mont., 1939 - May 2-16. Predicted dates - May 4-17, from last line of table 13.

Table 14.--Prediction of hatching period for Melanoplus sanguinipes at
Carson, N. Dak., 1945

5-day interval	Average maximum temperature $\bar{t}$	Current average maximum temperature t	Devia-tion $(t-\bar{t})$	Effect of 1-degree deviation a	Sum of $a(t-\bar{t})$	Hatching dates (10-90%)[1]
	° F.	° F.	° F.	Days	Days	
March 2-6----	26.0	21.4	-4.6	-0.473	2.18	June 9-28
7-11----	33.4	44.8	11.4	- .215	- .28	June 7-26
12-16----	41.3	52.4	11.1	- .034	- .65	June 6-25
17-21----	47.8	60.4	12.6	.079	.34	June 7-26
22-26----	50.1	58.4	8.3	.134	1.45	June 8-27
27-31----	52.7	52.0	- .7	.140	1.36	June 8-27
April 1-5----	47.9	39.2	- 8.7	.106	.43	June 7-26
6-10----	50.5	60.0	9.5	.041	.82	June 8-27
11-15----	53.9	51.0	- 2.9	- .044	.95	June 8-27
16-20----	61.9	54.2	- 7.7	- .142	2.04	June 9-28
21-25----	59.8	48.8	-11.0	- .242	4.73	June 12-July 1
26-30----	67.0	58.0	- 9.0	- .335	7.75	June 15-July 4
May 1-5----	67.3	61.2	- 6.1	- .412	10.26	June 17 -July 6
6-10----	62.3	52.2	-10.1	- .463	14.94	June 22 -July 11
11-15----	65.7	50.4	-15.3	- .480	22.28	June 29 -July 18
16-20----	70.8	55.8	-15.0	- .452	29.06	July 6-25
21-25----	70.7	70.0	- .7	- .371	29.32	July 6-25
26-30----	67.3	60.0	- 7.3	- .227	30.98	July 8-27
31-4----	70.9	56.0	-14.9	- .011	31.14	July 8-27
June 5-9----	71.9	54.0	-17.9	.287	26.00	July 3-22

1/ Average dates for 10-90 percent hatch - June 7-26, from table 8b.
Actual dates for 10-90 percent hatch, Carson, N. Dak., 1945 - July 2-23.
Predicted dates - July 3-22, from last line of table 14.